Large caverns, design and construction

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ABSTRACT: Instead of any recent discoveries, the cases presented support ideas matured along sixty years familiarity with underground works: depending on the depth, the most important factor of success is to find the best fit between the shape and orientation of a cavern on one hand, the anisotropies of the rock mass, and the stress field on the other one. Joints and faults play the first role at rather shallow depth; the behaviour of the rock mass under stress gains more importance with increasing depth. Collection of geological data is indeed the major prerequisite for any cavern design. Means for coping with high stress are recalled. As distance between caverns plays more in situ than into models, groups of caverns may be far less stable than isolated ones. Underground siting of any hazardous depots and activities brings the highest safety level, including for nuclear power plants.

1. INTRODUCTION

Instead of recent analyses and/or experiments, this short paper recalls sixty years personal familiarity with underground works, from coal mines and natural caves since 1945, hydroelectric plants since 1948, nuclear plants since 1964, and later water treatment plants in Scandinavia, metro works in various cities, storage caverns; not to mention the Mont Blanc road tunnel, the Channel tunnel and the Gjøvik Olympic cavern.

Wide-span caverns do exist in Nature: natural karstic caves are known worldwide (Gilli, 1984), up to 245 m span in France (La Verna, Figure 1), likely to host the Paris cathedral, and to 400 m in Sarawak; their long term stability is confirmed by age of calcite concretions on the floor and length of stalactites hanging from the ceiling (most of these caves being rather shallow). Many have plane ceilings, along stratigraphic joints, the biggest ones always display arched ceilings.

Mining caverns may reach big dimensions in a rather few cases (e.g. Tytyry, Finland), not much over 100 m; but long term stability was not sought by their users. Some mine openings are very deep, over 3 000 m in India, up to 4 000 in South Africa.

Conversely most civil underground openings need long term stability with a high level of safety, most are rather shallow (except tunnels under mountain chains: the Mont Blanc road tunnel is the deepest civil work, with a maximum depth 2 450 m).

2. SHAPES & FUNCTIONS OF CIVIL CAVERNS

Most civil underground openings are rather long horizontal tunnels or vertical shafts, with a smaller cross-section. When most cross sections of shafts keep close to a circle or a square, cross sections of horizontal caverns often deviates from such isodiametric cross section, in being flatter, as the Gjøvik ice-rink cavern or slender as some pump and storage hydropower plants.

The shape may depend on the material a cavern has to accommodate. Conversely, caverns for storage of fluids only need a gross volume, whatever their shape; no surprise this shape is governed by cost, mainly the cost of excavation and support: so "the best shape needs the less support". The room and pillar design of many mines suits to many functions, whatever rock pillars or manufactured ones (Paris Banque de France safe).

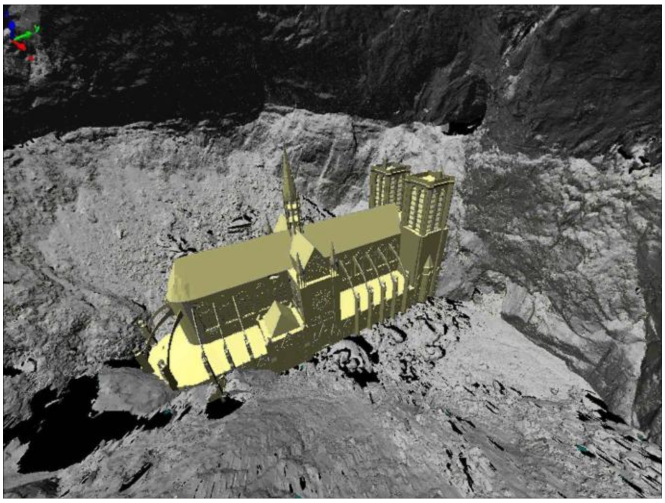

Figure 1: La Verna cave (Pyrénées range) scanned by ATM-3D (volume 3.6 hm^3)

The structure of the rock mass plays a major role at rather shallow depth: miners follow their coal seam/ore lode, they try not to win any piece of "sterile rock"; they cut across the rock mass as if they separate stamps from a board along their perforated borders. Winning sedimentary ore leaves extended caverns between parallel strata. Greek philosopher Platoon said that "chickens must be cut along their articulations", that's exactly what miners use to do.

At depth, that is when the stress level around is significant by reference to the rock strength, joints and faults leave the first place to the behaviour, either brittle or ductile: brittle behaviour implies rock bursts (South Africa mines, Mont Blanc and Lötschberg tunnels), and ductile behaviour shows itself by local deformations of the rock; mixed mechanisms may occur as 3.2 and Figure 3 opposite.

3. SOME KEY EXAMPLES

3.1 Early underground power plants of EDF

The early fifties were in France a booming era for hydropower; through dams, tunnels and underground plants. From a total number about 50 today, a dozen were in construction at this period. As soon as 1954, the author could write an unpublished report asking for many changes about these caverns:
i) use moderate blasting to preserve the quality of the rock all around the final volume (after others and after presplitting, Hoek, 2006, will stress this point);
ii) provide rounded angles and chamfers instead of acute angles, either positive or negative;
iii) escape the "mushroom" shape (so named in Japan for the "head" is wider than the "foot", the main part);
iv) prefer ovoid shape to high vertical walls (Figure 2);
v) escape multiple caverns too close from each other;
vi) anchor the tracks of overhead cranes to the walls, instead of supporting them upon high pillars.

About the location by respect to faults and joints, it appeared better to cross at right angle the "more dangerous family" than to try to cope with two or more. The practice of mapping all joints and faults by their poles on a spherical graph (Schmidt or Wulf) is useful to select the attitudes of all faces of caverns; but the extreme values are more significant than the averages: one must actually mind "the wrong joint at the wrong place", and try to escape it! Of course, 3D models may help find the best location.

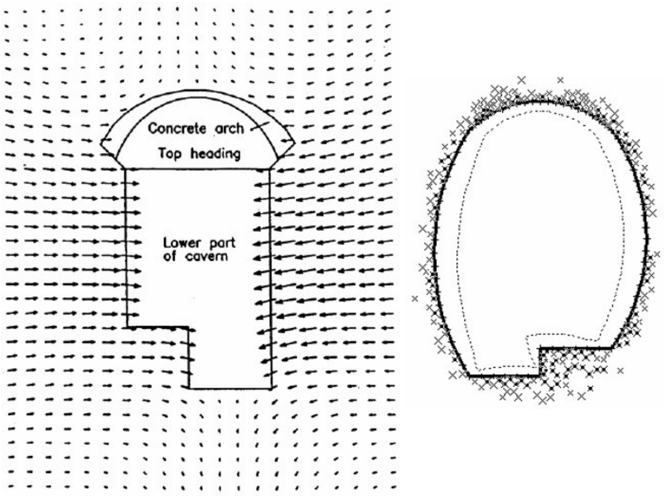

Figure 2: Displacements around a standard cross section showing the deformation of vertical walls, and a preferred shape, closer to an ovoid (after Evert Hoek, the document on the Internet was replaced by updated notes, 2006, from which the ovoid has unfortunately disappeared)

3.2 Lanoux-l'Hospitalet tunnel in slaty rocks

This pressure tunnel, bored 1955-58, had to bring water from Lanoux reservoir to l'Hospitalet plant (Duffaut, 1981). The rock was a low metamorphic slate, very hard, but crisscrossed with faults; the dip of schistosity joints was sub vertical and the tunnel direction was very close to the strike. As soon as the rock cover exceeded 300 m, extensive brittle failures of the slates appeared on both sides, which called for support by steel plates and/or ribs (Figure 3). When the tunnel was bored through, and concreting began, one noticed the supports had so much deformed that the template was engaged over long sections: some extra excavation was needed.

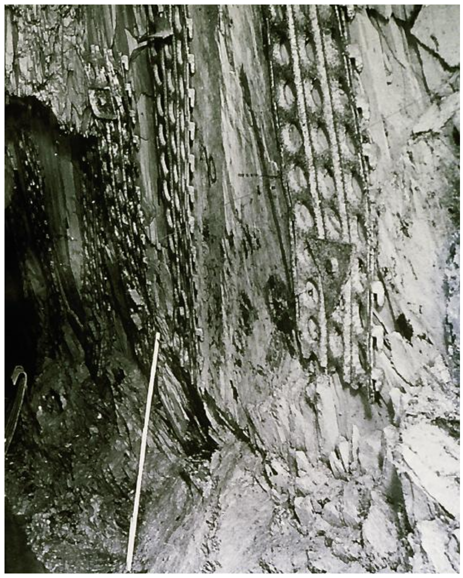

Figure 3: Buckling of slaty rocks deformed the bolted steel plates along Lanoux-L'Hospitalet tunnel (photo P. Duffaut, 1958)

The good surprise was no rock fall occurred: the rock mass had completed its deformation and the hole become compatible with the stress field around, thanks to the Fenner plastic annulus which had automatically played its role.

3.3 From Snowy Mountains Poatina, Australia, to la Réunion island Takamaka

A small power plant being dug at la Réunion Island (Indian Ocean) inside basaltic rocks under high stress, the author suggested to use a trick experimented at Poatina underground power plant in Australia and derived from a well known practice in iron ore mines of north-eastern France: in order to mitigate brittle failure: close parallel boreholes were bored along a line of the arch loins, which helped to shorten the perimeter, then to relieve the excess of stress.

This method, first applied along sharp angles of the perimeter, between plane faces, can be extended to any critical points where stress happen to concentrate and even to the whole contour : along a circular contour, the virgin stress anisotropy will call for a pair of cuts in the plane perpendicular to the maximum stress component.

Other tricks may play about the same role (Figure 4 from Duffaut, 1974).

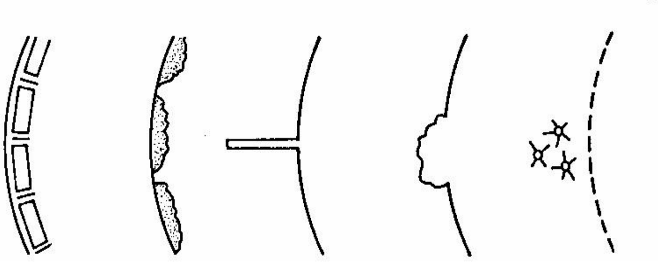

Figure 4: Five tricks to reduce stress concentration around a deep tunnel: centre, deep cut; right, local overbreak or blasted boreholes, left Tauern tunnel shotcrete with uncovered spaces, or wooden planks inserted between concrete blocks

3.4 Chalk

In the early seventies, EDF studied a pump and storage plant east of Paris, with an underground machine hall. Though the project had moved to Revin, farther from Paris, it brought a lot of data on this light and soft rock. (Dessenne et al. 1969). Pure chalk is a high porosity rock, about 30-40 %, so very light and easy to cut Thanks to its void content it can lose volume through a plastic like deformation

3.5 Gjøvik ice rink cavern

In Norway, the 1994 Winter Olympic Games provided the opportunity of reviving a project of the seventies: a large underground ice rink intended to validate caverns big enough to host nuclear power plants of standard size, about 1000 MW (electric output). Norway having abandoned nuclear power, the project was dormant for two decades, then built in the early nineties.

The arched roof cavern is 61 m wide, 25 m high, and 91 m long, providing 5800 seats around the rink. It was dug inside a granite hill just behind the city, with a rock cover less than the span (about 25-50 m). The rock quality was well known through former caverns, and no surprise was met during the works. The only "support" is a fibre reinforced shotcrete layer, 10-15 cm thick, and 6 m rock bolts every 2.5 m. This success puts an end to the previous taboo on wide span caverns.

3.6 Heathrow tunnel failure

A cave-in occurred in Oct. 1994 inside Heathrow airport over construction works of the Express rail link. Close to an access shaft, three parallel tunnels were to form an underground station, two platform tunnels on either side of a central concourse tunnel, all built along NATM principles: keeping his confidence from parallel galleries of the Channel tunnel works at Folkestone Cliff, the Austrian engineer in charge had confused London clay with Channel chalk; the former is a true rock, even very weak, not the latter, whatever hard it may look. One may know NATM cannot tackle tunnels at shallow depth. In addition, the expertise revealed minor defects in the shotcrete, and the more, the signal given by surface settlements had been neglected.

A lesson seems to have been missed: one tunnel does not cause any disturbance very far, two tunnels are known to produce greater settlements, the case of three tunnels was not so well documented, but we must recall the motto of road safety in France: one glass wine may be OK, three glasses are not: "un verre ça va, trois verres, bonjour les dégâts". A lesson recalled below.

3.7 Chillida underground sculptural project

Spanish sculptor Chillida (deceased 2002) designed a cavern close to a huge hollow cube about 40 m side (Figure 5), with plane faces and sharp angles (none exactly 90°) to be carved inside an ancient volcano of Fuerteventura (Spanish Canaries) with 2 vertical shafts towards sun and moon, and horizontal gallery towards horizon on sea. Though declared feasible by a leading design bureau in 2004, it seems now to be abandoned. Clearly, the shape of this cavern is just counter Nature!

Figure 5: Tindaya, a negative sculpture designed by Spanish sculptor Chillida: a hollow cube, 64 000 m^3. Two persons give the scale (The Internet).

4. APPLICATIONS

4.1 Caverns for neutrino research

The author was glad to attend a symposium on neutrino research at Aussois, France, NNN05).

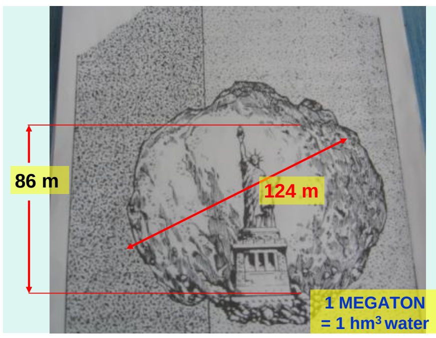

Figure 6: the Megaton cavern could host the Liberty

He took interest for the Megaton project (1 000 000 m^3 at 2000 m depth), now revived by LAGUNA project (figure 7). All three caverns are axi-symmetrical: The cross section of GLACIER cavern is but a little wider than the Gjøvik ice rink cavern, its horizontal floor could be critical. LENA appears as a vertical shaft which does not raise any special concern.

The vertical walls of MEMPHYS do appear more problematic: a rounded cross section would fit better high initial stresses. As three caverns are necessary to provide the needed volume, the true problem lies in their distance (see Heathrow failure, 3.6 above).

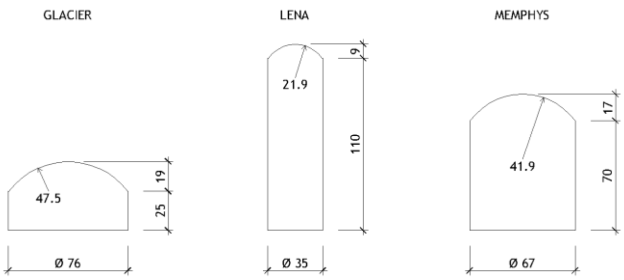

Figure 7: Shapes and dimensions of three axi-symmetrical caverns designed for the LAGUNA experiment (Mosca, 2010)

4.2 Applications to any dangerous plants including underground nuclear power plants

The catastrophic explosion of nitrates in a Toulouse chemical factory (Sept 21, 2001) called attention on the safety provided by a location underground, a practice formerly classical for factories and depots of explosives which nuclear tests have confirmed (Duffaut, 2002). Hydrocarbons are stored in caverns since about a half century and nuclear waste will follow.

In the early sixties, the USSR built underground nuclear power plants in Siberia for its secret nuclear weapons complex. In France, Chooz has been the only civil underground plant operated 1972-1991 (being now dismantled (Duffaut, 2007). The Fukushima event makes urgent to site anew underground nuclear plants or at least their nuclear parts (Figure 8).

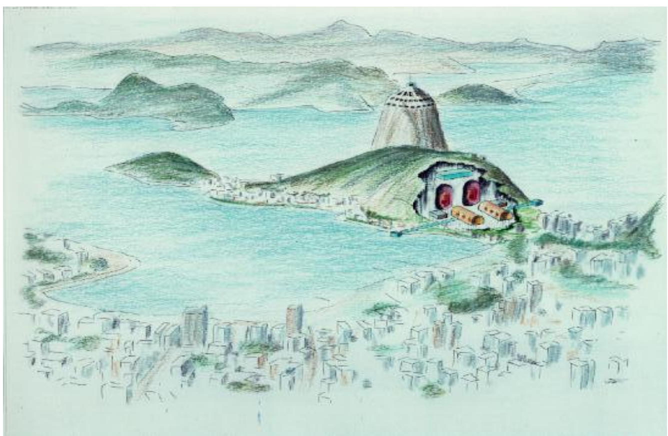

Figure 8: A sound rock relief would provide a sound location for a nuclear power station

5. CONCLUSIONS

5.1 Geology and physical fields

No human work is more dependent on geology than underground works. They are fully embedded in the Earth crust, with its natural departures of continuity, isotropy and homogeneity. The scale of caverns is far from the scale of samples brought in the lab: When a rock is made of crystals and voids, rock masses are made of joints, faults, and various rock blocks in between. They are submitted to all its natural fields, gravity, tectonic stress and movements, heat transfer, water forces and chemical interactions, electric and magnetic fields, etc. (Duffaut, 2000). Long before the stresses were known and understood, miners knew that the more stable cross sections were slender in the Alps and flatter in Scandinavia.

Geology governs all underground works, far more than any other ones: Build with Nature, not against it!

5.2 Summary

Very often cavern stability is misunderstood in the community of civil engineers, accustomed to bridges and buildings made of slender members. Below the surface many rules will change: only mining engineers can easily tackle underground works inside an infinite medium, the more the greater depth. Huge caverns are feasible, the more where a good fit is available with geological structures and stress fields.

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